SECTION 3

ACCOMMODATION OF BSS IN THE 2300-2410 MHz RANGE

INTRODUCTION

This section contains an analysis of the feasibility of accommodating BSS in the 2300-2410 MHz range. NTIA measured the emission characteristics of the ISM environment and analyzed the results to determine whether a segment of the range was suitable for BSS. Procedures and results of spectrum measurements performed by ITS are presented, and the measured levels are compared against the BSS receiver interference threshold, as determined from CCIR Report 955-2 and CCIR Document JIWP92/115-E. A description of NTIA computations is provided in the appendix.

KITCHEN ENVIRONMENT

Three different forms of measurements were performed to identify the potential interference from a microwave oven to a BSS receiver in the kitchen area. All were performed at a distance of 3 meters and consisted of 2300-2600 MHz emission spectra, radiation patterns, and time waveforms.

Emission Spectra

Using a peak detector and 300 kHz bandwidth[2], the entire 2300-2600 MHz band was swept in 50 milliseconds, measuring power in dBm. The sweeps were continued for 5 minutes holding the peak values. A real-time view revealed erratic generation of frequency spikes at frequencies throughout the band. Therefore, the emission characteristics shown in Figure 3-1 represent the peak hold envelope measured over a 5 minute period. Seven ovens were measured, the figure showing four representative examples. Measurements of each oven confirmed the primary operating frequency to be near 2450 MHz. Secondary regions of high signal strength appeared on most ovens between 2350 MHz and 2380 MHz, and near 2550 MHz. The frequency and amplitude of the second "hump" on the lower side appeared to be affected by load. Smaller loads increased the levels at lower frequencies. Therefore, measured levels shown in Figure 3-1 may not represent the absolute worst case for the ovens

2 An individual BSS channel will probably be on the order of 300 kHz.

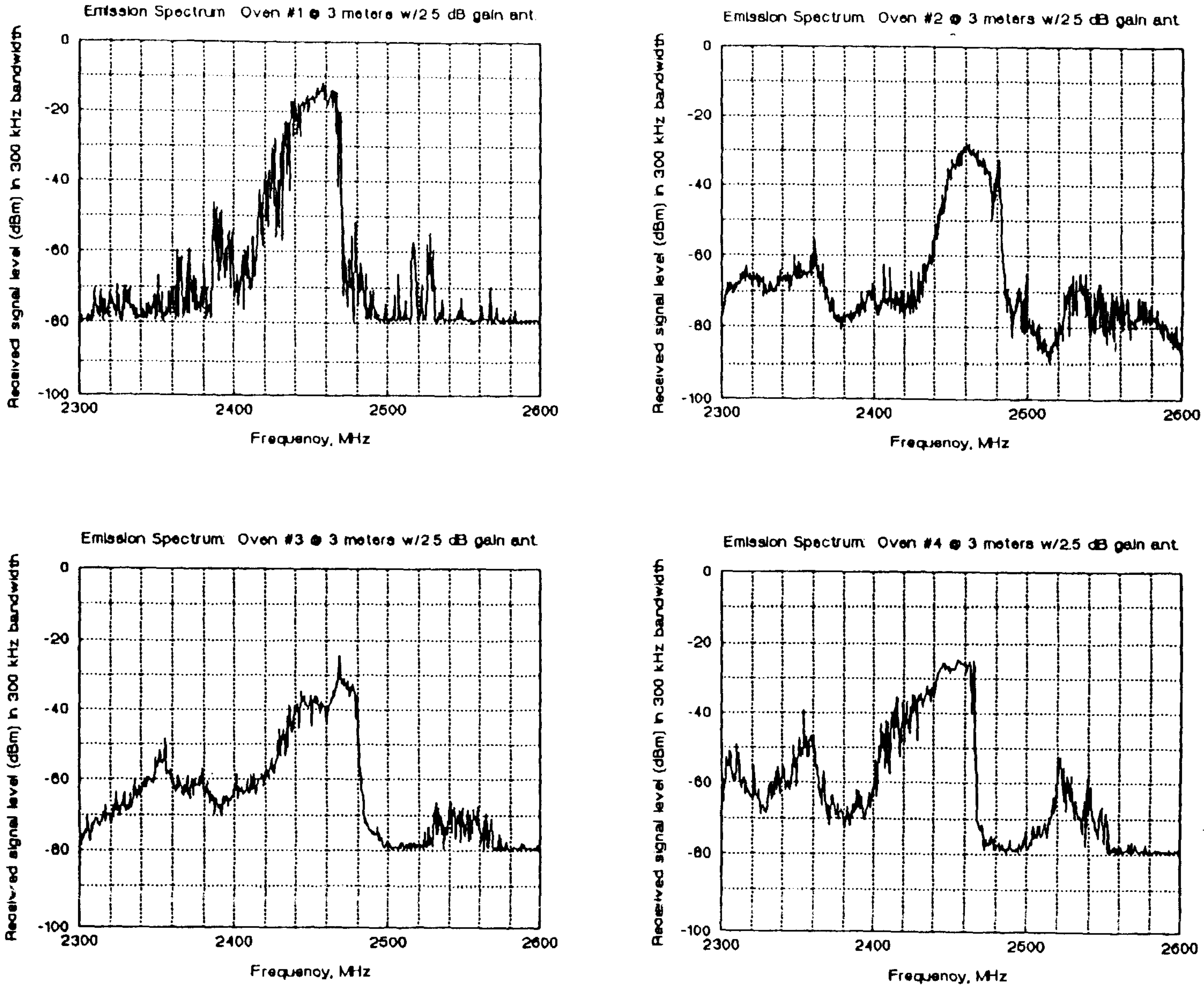

Figure 3-1. Individual emission spectra

tested. Though the measurement system floor in these examples is around -80 dBm, much of the spectrum is well above that level.

Analysis of CCIR data indicates that the BSS receiver interference threshold is approximately -115 dBm or -125 dBm (See Appendix page 8 - 300 kHz bandwidth). Peak levels throughout the 2300-2500 MHz portion of the measured range exceed those values.

Radiation Patterns

Two of the ovens were taken to an antenna range clear of reflecting objects. Cables to the test equipment were run underground to a measurement recording location. The ovens were set on a turntable and rotated 360°, stopping every 3° for 1 second. A peak detector was used. The result is a radiation pattern made up of 120 points, each point being the peak sampled in 1 second of oven operation. These measurements were performed with the oven on its base, its side, and its back, providing three orthogonal views. Figure 3-2 provides one example. Since the object of the measurement was to determine the relative strength of the signal at various azimuths, the figure shows power relative to the maximum recorded.

These measurements reveal the ovens to be generally omnidirectional. Reflective surfaces in the kitchen areas would only serve to make them more so. Therefore, little improvement will be gained through positioning the BSS receiver or the microwave oven.

Time Waveforms

Time waveform measurements were taken of 60 second, 1 second, and 50 millisecond duration. The longer time traces reveal that oven power is actually determined by a timer that varies the amount of time that the magnetron is on and off during the cooking period. One oven pulsed continually on the high power setting. The 50 millisecond time traces show the actual waveform of the individual pulses. For these time traces, seven measurement frequencies, 2410, 2390, 2360, 2350, 2330, 2310, and 2300 MHz (Figures 3-3 through 3-9 respectively), were selected within the band of interest to BSS. Since the spectrum analyzer was tuned to a specific frequency for this set of measurements and the magnetron continually varied its frequency during operation, the incoming signal was often tuned off the receiver. Therefore, only portions of its spectral content are seen, two spikes containing the leading and trailing edge of the rectangular pulses, while the strength of the measured pulse has fallen away.

Since the ovens constantly vary in frequency, several "snapshots" were taken at each frequency for each oven. Figures 3-3 through 3-9 represent the worst of those "snapshots" for each oven/frequency combination.

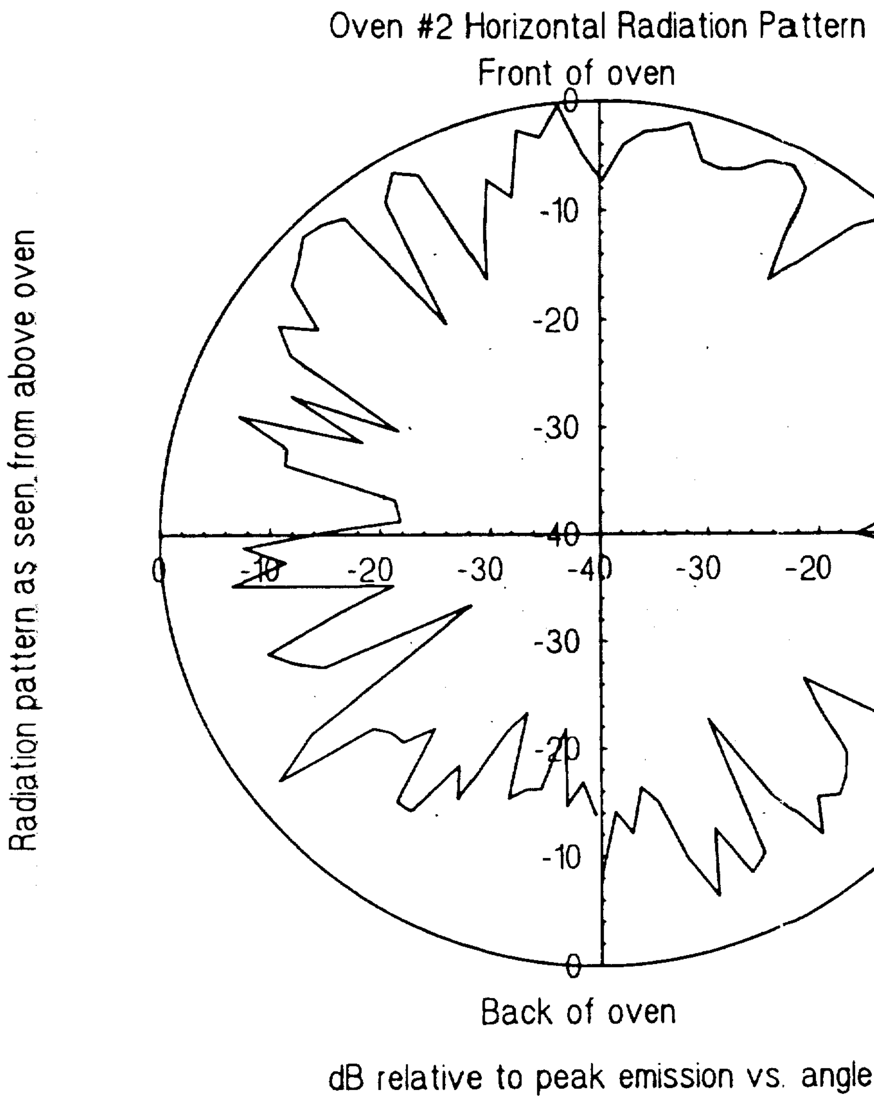

Figure 3-2. Microwave oven radiation pattern

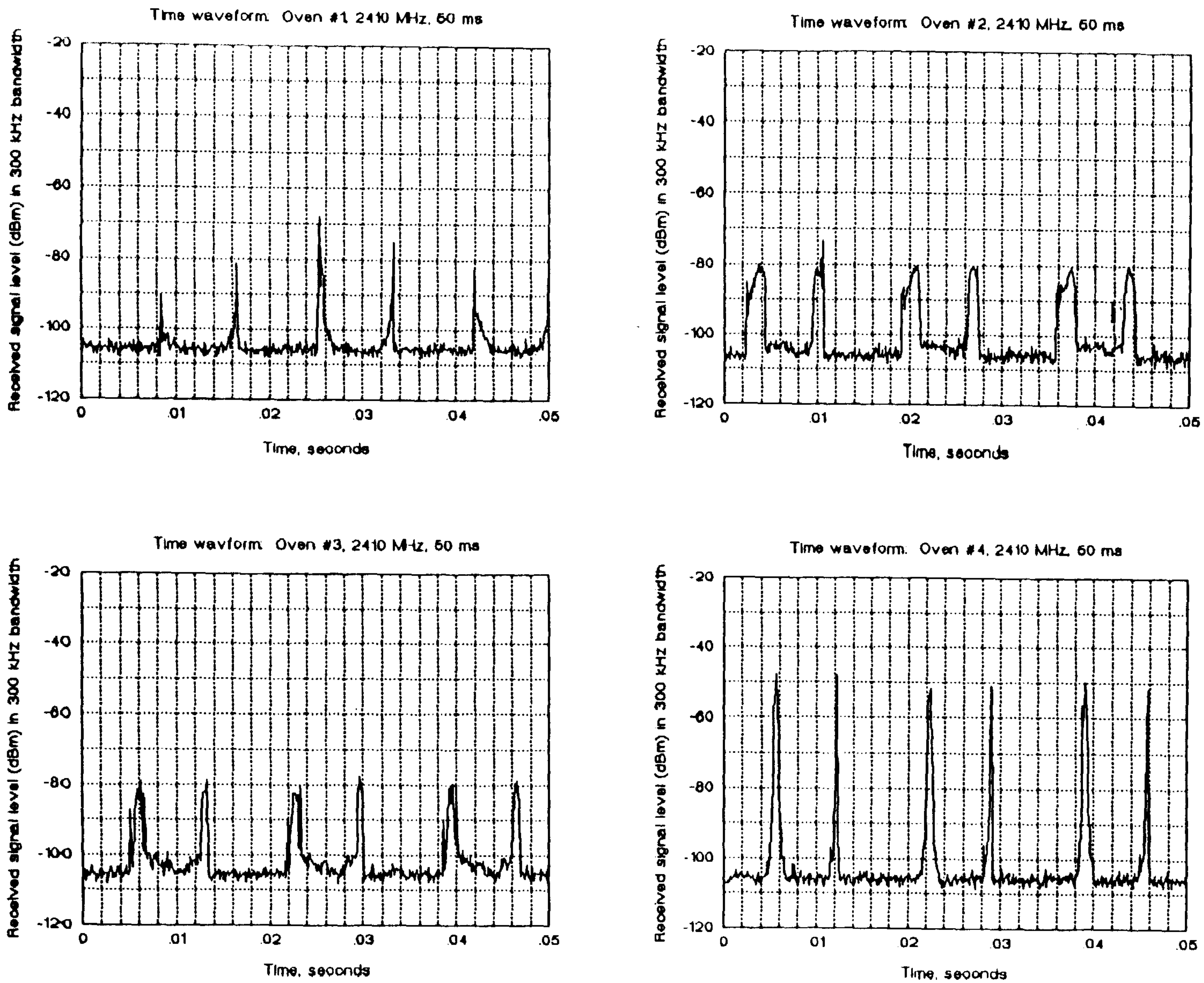

Figure 3-3. Time waveforms 2410 MHz

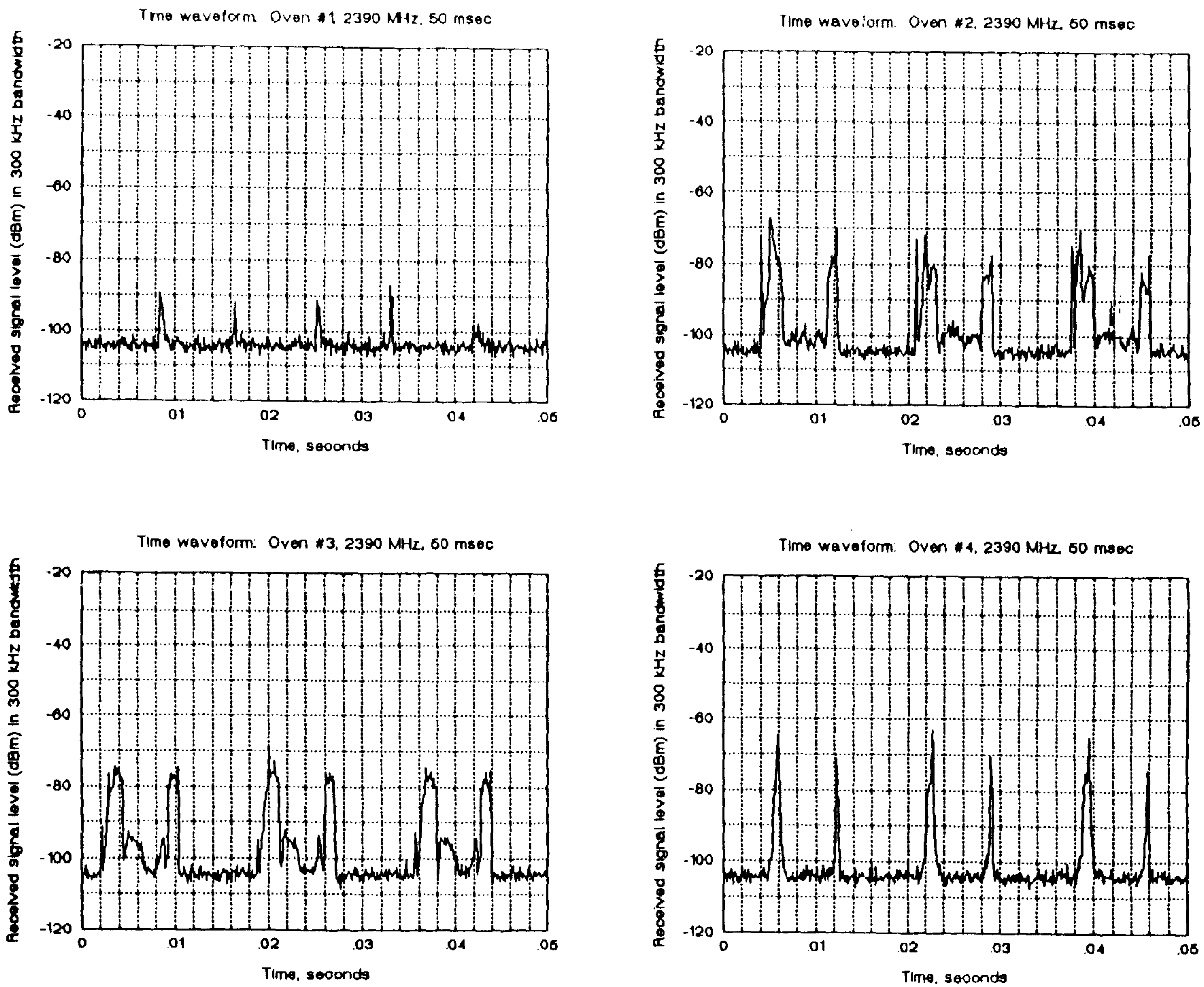

Figure 3-4. Time waveforms 2390 MHz

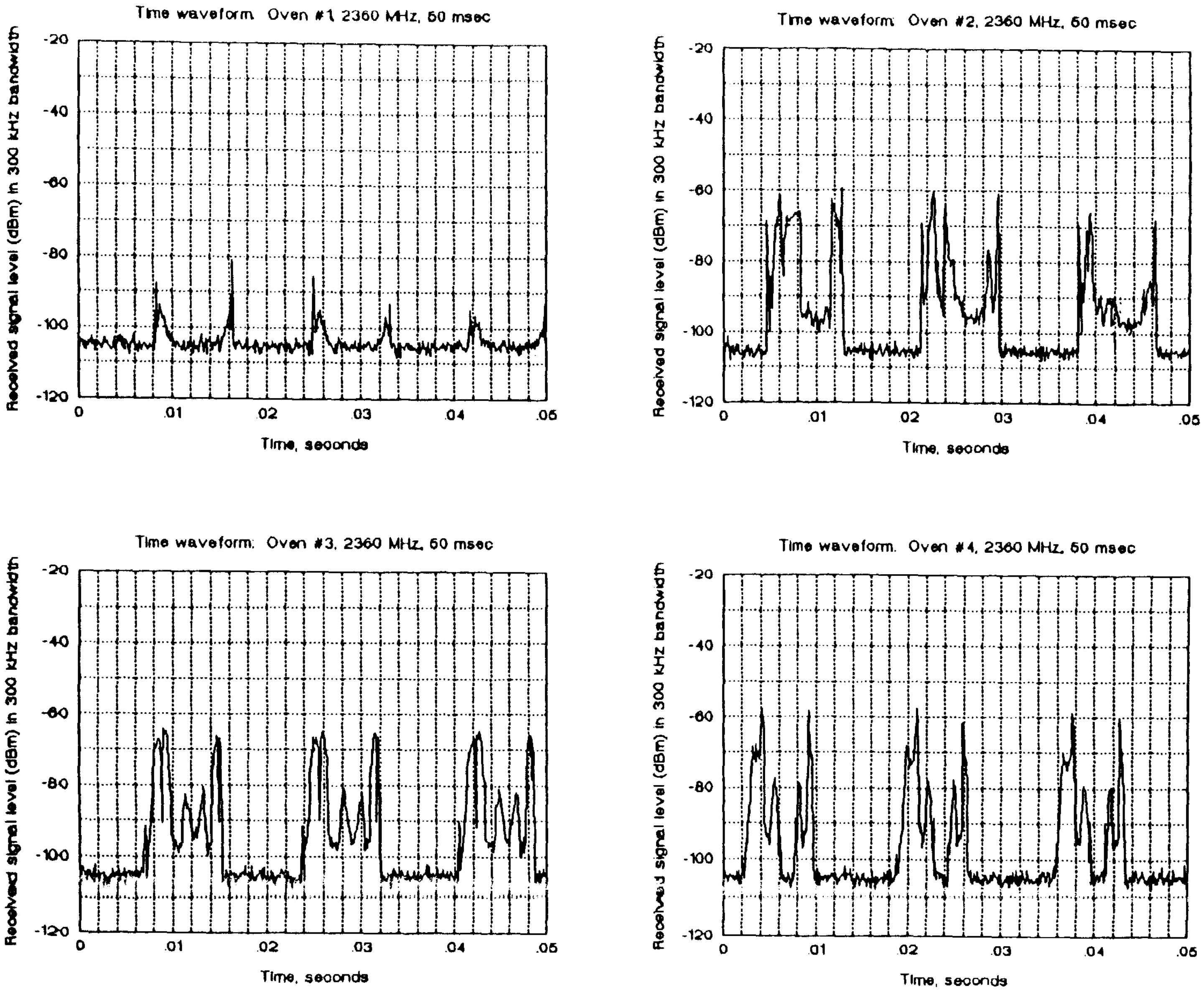

Figure 3-5. Time waveforms 2360 MHz

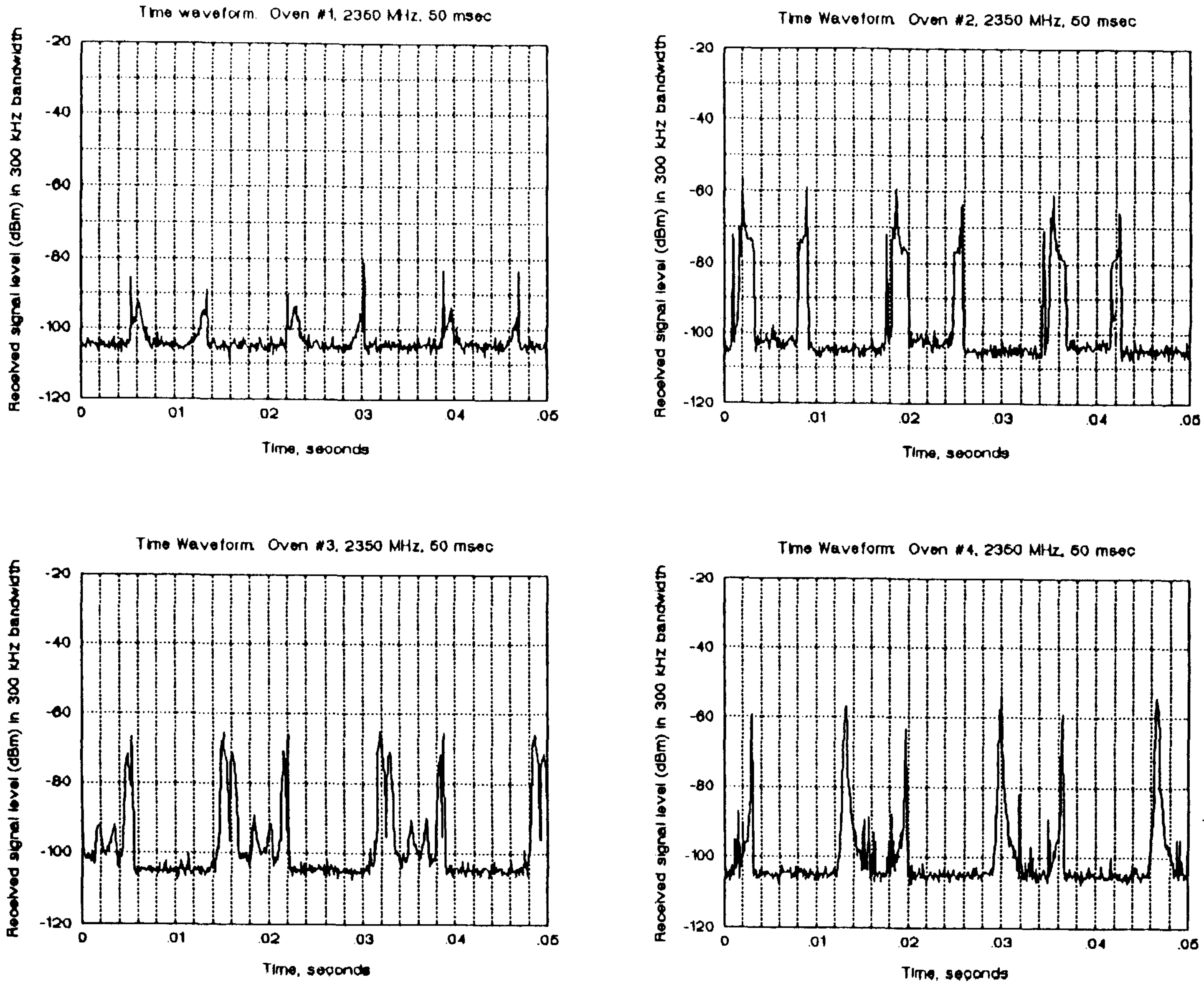

Figure 3-6. Time waveforms 2350 MHz

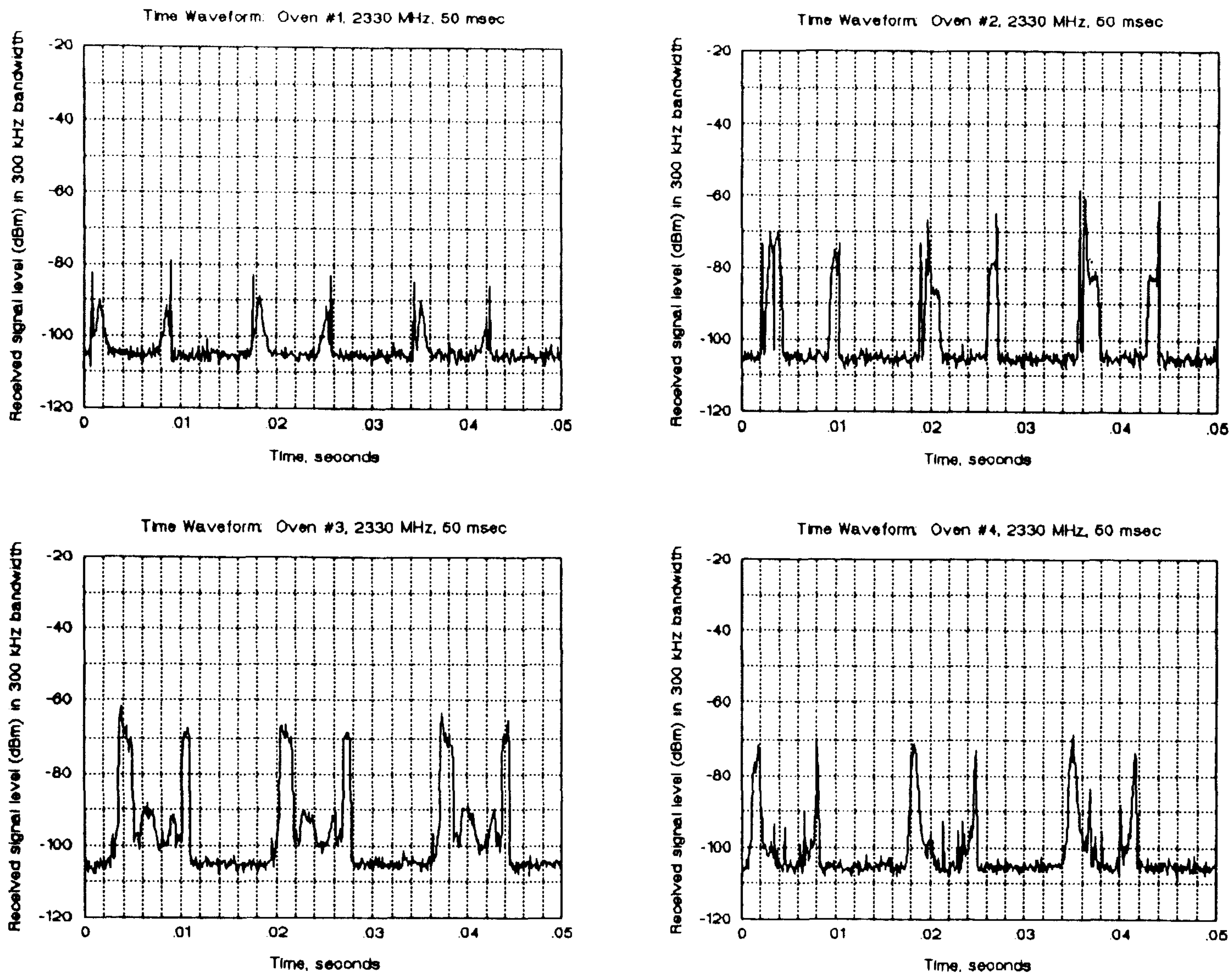

Figure 3-7. Time waveforms 2330 MHz

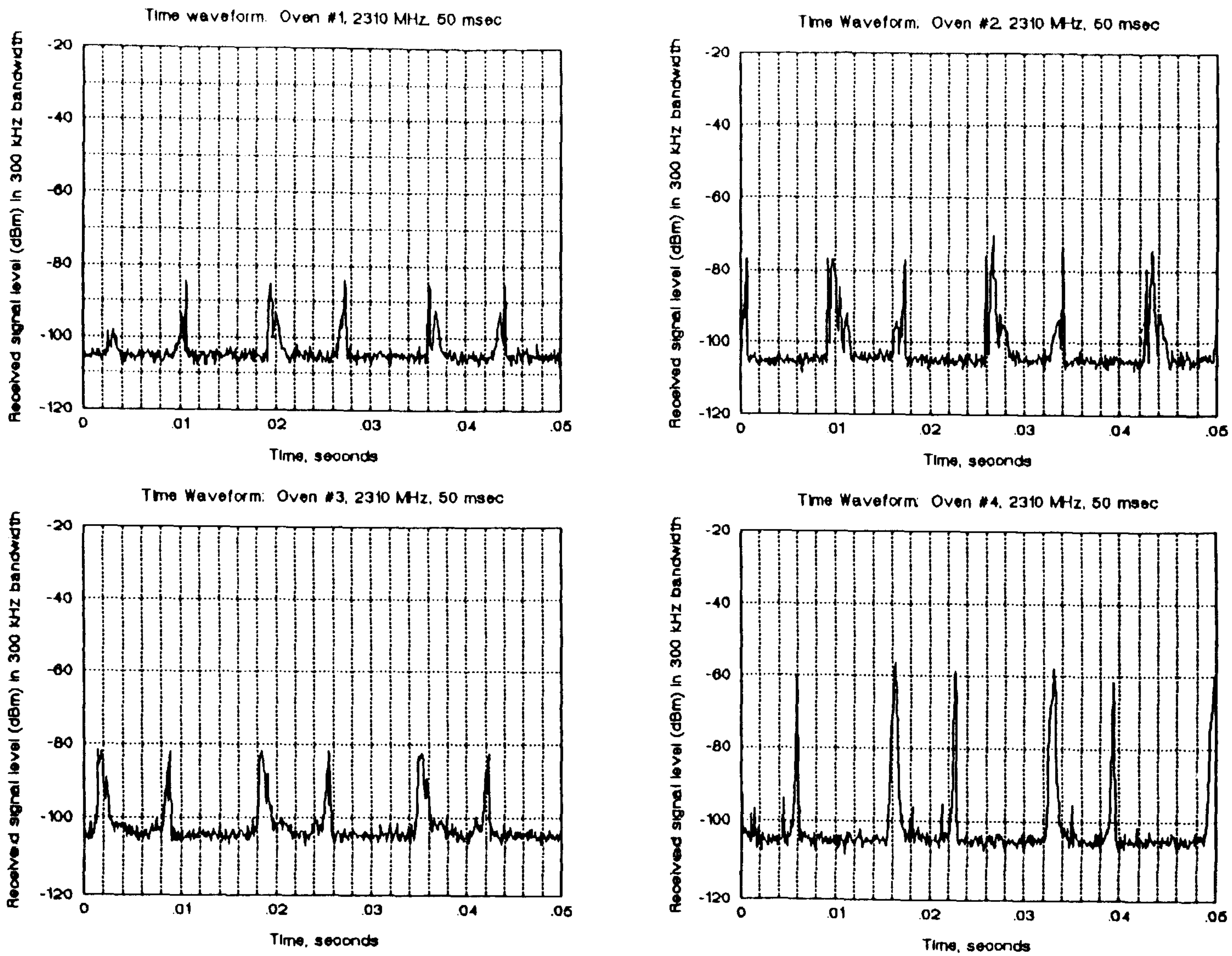

Figure 3-8. Time waveforms 2310 MHz

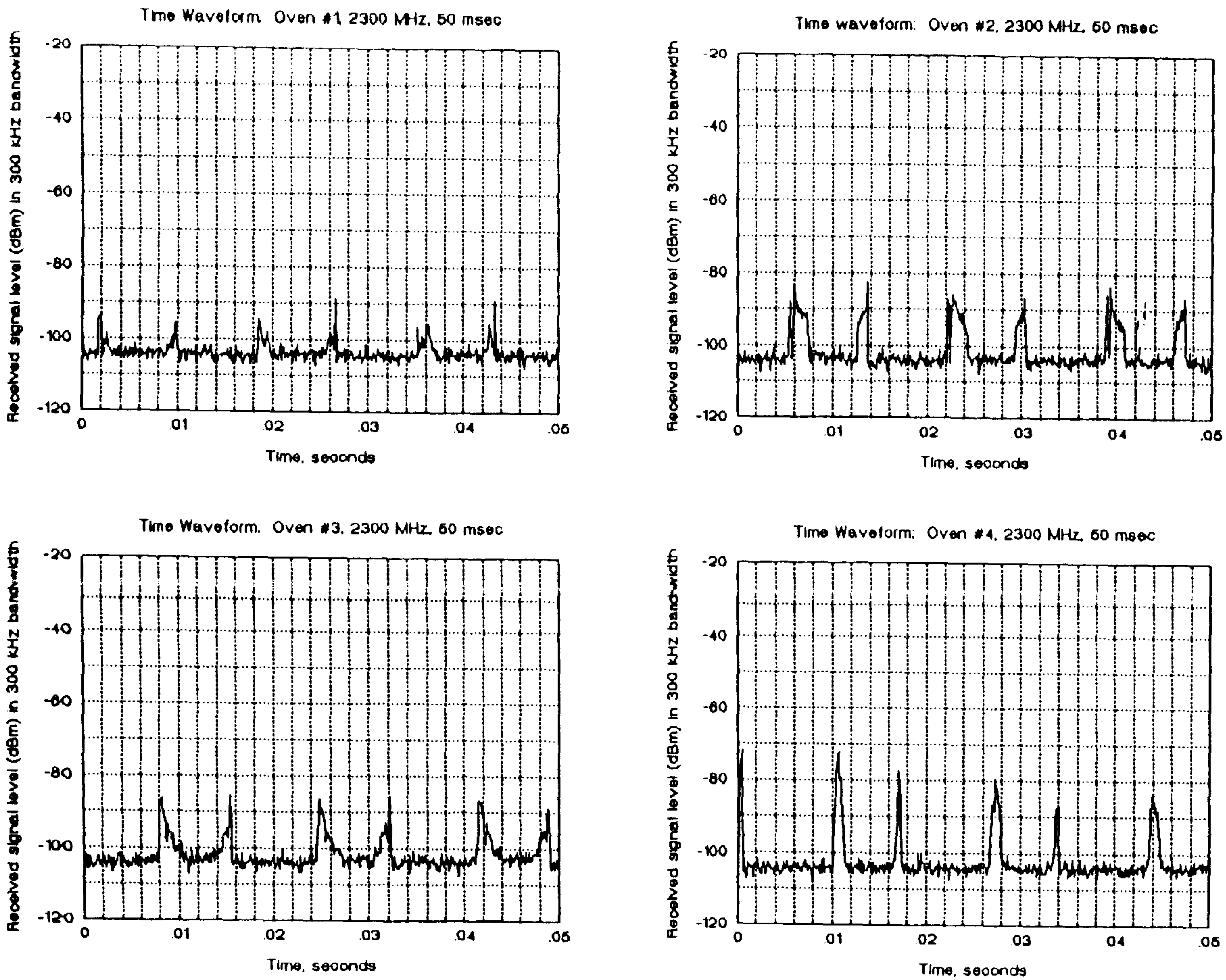

Figure 3-9. Time waveforms 2300 MHz

The same four ovens, for which emission spectra were taken, were used for these measurements. The plots reveal some significant characteristics. First, the pulse periods all appear about the same, regardless of the oven. They emit 8 millisecond pulses with just under 50% duty cycle. Second, more of the pulse energy is identifiable at the frequencies near 2350 MHz than at 2390 or 2410. This indicates that, for the ovens tested, the pulses were often being emitted nearer 2350 MHz. The existence of the secondary hump near 2350-2380 MHz in each of the ovens shown in Figure 3-1 may provide some confirmation of these time waveforms. The further below 2350 MHz the measurements were performed, the more impulsive the pulses appear.

The data shows, that for all ovens and at all frequencies of interest, portions of the microwave oven pulses rise above the BSS threshold derived from CCIR documents. For some of the ovens and at some frequencies, the entire pulse is above the calculated thresholds. Considering the pulse duty cycle, the BSS data stream could be interrupted almost 50% of the time in those cases. At lower frequencies and for some ovens, the amplitude and probability of occurrence of microwave oven pulses decreases, and are off-tuned (receiver responses show impulse spikes coincident with the beginning and ending of each pulse), but peaks are still above the threshold. In some cases, the impulse responses broaden at their base to 1-2 milliseconds duration. The proposed designs could enable BSS receivers to work in this environment. Further advantages will be gained if the microwave oven out-of-band emissions are reduced.

APARTMENT INTERIOR ENVIRONMENT

Aggregate emission spectra measurements were taken inside an apartment in Boulder to give an example of what a BSS receiver might experience from external ISM sources in a residential environment.

Like the individual oven tests, a peak detector and 300 kHz bandwidth, were used to measure the entire 2300-2600 MHz band. The band was swept in 50 ms, measuring power in dBm. In this case, the sweeps were continued for a period of 1 minute holding the peak values. At the end of a minute, the maximum levels were recorded in a data file as a single scan. During a 24 hour Friday-Saturday weekend period, 158 scans of this type were recorded.[3]

3 Due to need for measurements in other bandwidths, the bandwidth of the measurement device was cycled from 300 to 100 to 30 to 10 kHz. A period of 24 hour measurements for one bandwidth only represents a quarter of that period. Therefore, some variation may exist between bandwidths due to the time difference. The reception of the aggregate signal in the area lessens the probability that exceptional variation would be missed. However, the presence or absence of signals in a next-door apartment might significantly change the maximum peaks experienced.

The resulting data were then used to determine the maximum peak, mean peak, and minimum peak signal levels received at each frequency. Therefore, the minimum levels shown in Figure 3-10 are actually the minimum peaks taken during the many scans (a scan consisting of many sweeps). The other curves could be referred to as the maximum peaks, and mean peaks.

Figure 3-10 shows the results from a portion of that 24 hours, 6:30-9:30 PM Saturday, a period that was thought to be "busy".

In the 2300-2410 MHz range, the maximum and mean peak levels are consistently above the calculated BSS interference threshold. The mean values are also very close to the peaks, indicating that values near the peaks were frequently reached. Assuming the time waveforms of the ovens near this particular apartment to be similar to those in Figures 3-3 through 3-9, the BSS receivers could be affected above 2350 MHz.

APARTMENT COMPLEX EXTERIOR ENVIRONMENT

Measurements were taken outside an apartment complex to give an example of what a mobile receiver might experience on the street. These measurements were completed in three parts: aggregate emission spectra, aggregate signal amplitude distributions at fixed frequencies, and time waveforms at fixed frequencies.

Aggregate Emission Spectra

These tests were performed exactly like those completed inside the apartment. During a 24 hour weekday period, 233 scans were recorded. The data shown in Figure 3-11 represent the 4:30-7:30 PM dinner period. Once again, it demonstrates that the maximum peak and mean peak values of the microwave oven emissions between 2300 and 2410 MHz exceed the BSS calculated threshold.

Aggregate Signal Amplitude Distributions

For these measurements, three 5-minute breaks were taken from the emission spectrum measurements, and the receiver was set for specific frequencies, 2370 MHz, 2390 MHz, and 2410 MHz, using a 300 kHz bandwidth. The 5-minute periods were all taken during the dinner time (4:30-7:30 PM). During these 5-minute periods, 5000 samples were taken of the incoming

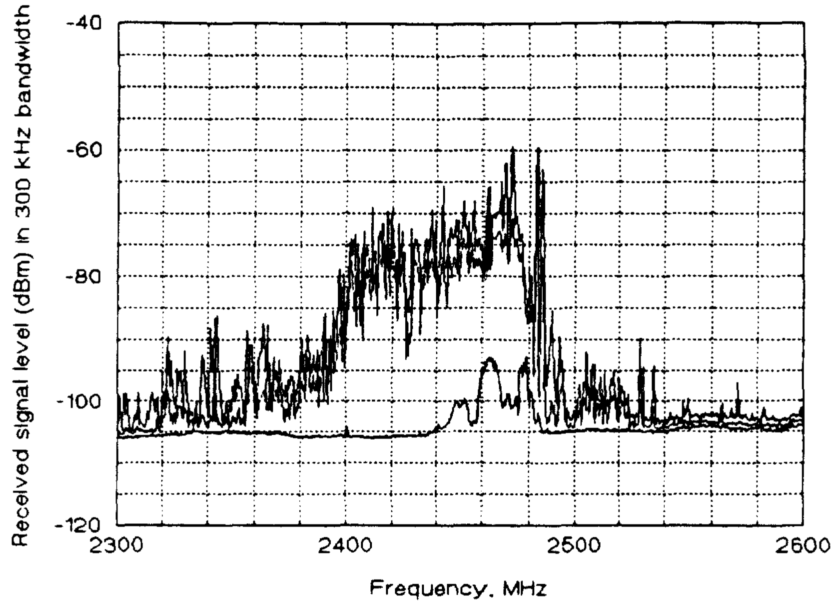

Figure 3-10. Aggregate emission spectrum inside apartment 6:30-9:30 PM Saturday

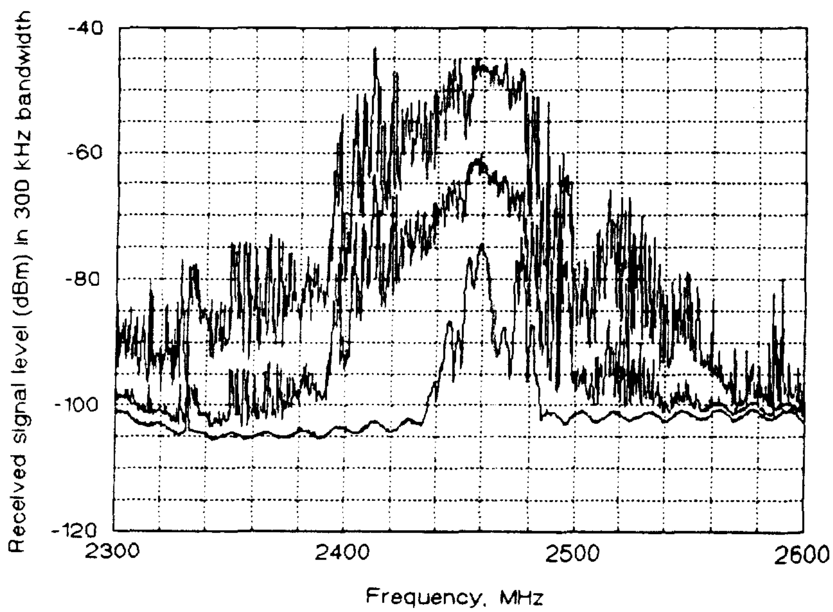

Figure 3-11. Aggregate emission spectrum outside apartment complex 4:30 -7:30 PM weekday

signal level. These levels were then used to determine an aggregate amplitude probability distribution (APD). The results are shown in Figure 3-12. Levels higher than -102 dBm were present from 30-50% of the time depending on the frequency. The lowest frequency measured, 2370 MHz, similar to the individual oven measurements (See Figure 3-1), had the highest received signal level for a given abscissa value.

Aggregate Time Waveforms

Time waveforms of 60-second lengths were recorded during the 5-minute periods mentioned above to provide aggregate waveforms. Figure 3-13 shows what appear to be the emissions of two or more ovens. Measured at 2370 MHz, the signal between 0 and 35 seconds shows the lobing characteristics, possibly associated with an oven with a rotating tray. At 52 seconds, a single oven, probably close by, emitted consistently high levels. In between these two may be a period where only more distant ovens are on, no ovens are on, or the first oven may have drifted away from 2370 MHz as it cooked.

ANALYSIS SUMMARY

Above 2350 MHz, the probability is high that the BSS receiver will detect microwave oven pulses consistently above its threshold in any of its intended operating environments. Many of the pulses will be tuned off of the BSS frequency, but time waveform measurements and APDs show that the percentage of time above threshold to be significant. Below 2350 MHz, pulse amplitudes are lower, but still above the threshold at short distances in a home or between apartments. Also, only the leading and trailing edges of the pulses will be detected by the receiver. As distances increase, the percentage of peaks at lower frequencies exceeding the threshold will decrease.

French equipment developers have indicated that BSS system capabilities allow it to perform in the presence of interference spikes, and yet they have stated that a carrier-to-interference ratio of +7 dB is necessary in the presence of impulsive interference.[4] Analysis of data drawn from CCIR Report 955-2 and CCIR Document JIWP92/115-E indicates that the BSS receiver interference threshold is approximately -115 dBm or -125 dBm (See Appendix). Therefore, BSS system designers must take the presence of microwave oven emissions into consideration in their receiver design.

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4 Conversation between C. Filippi (NTIA) and D. Pommier, June 7, 1991.

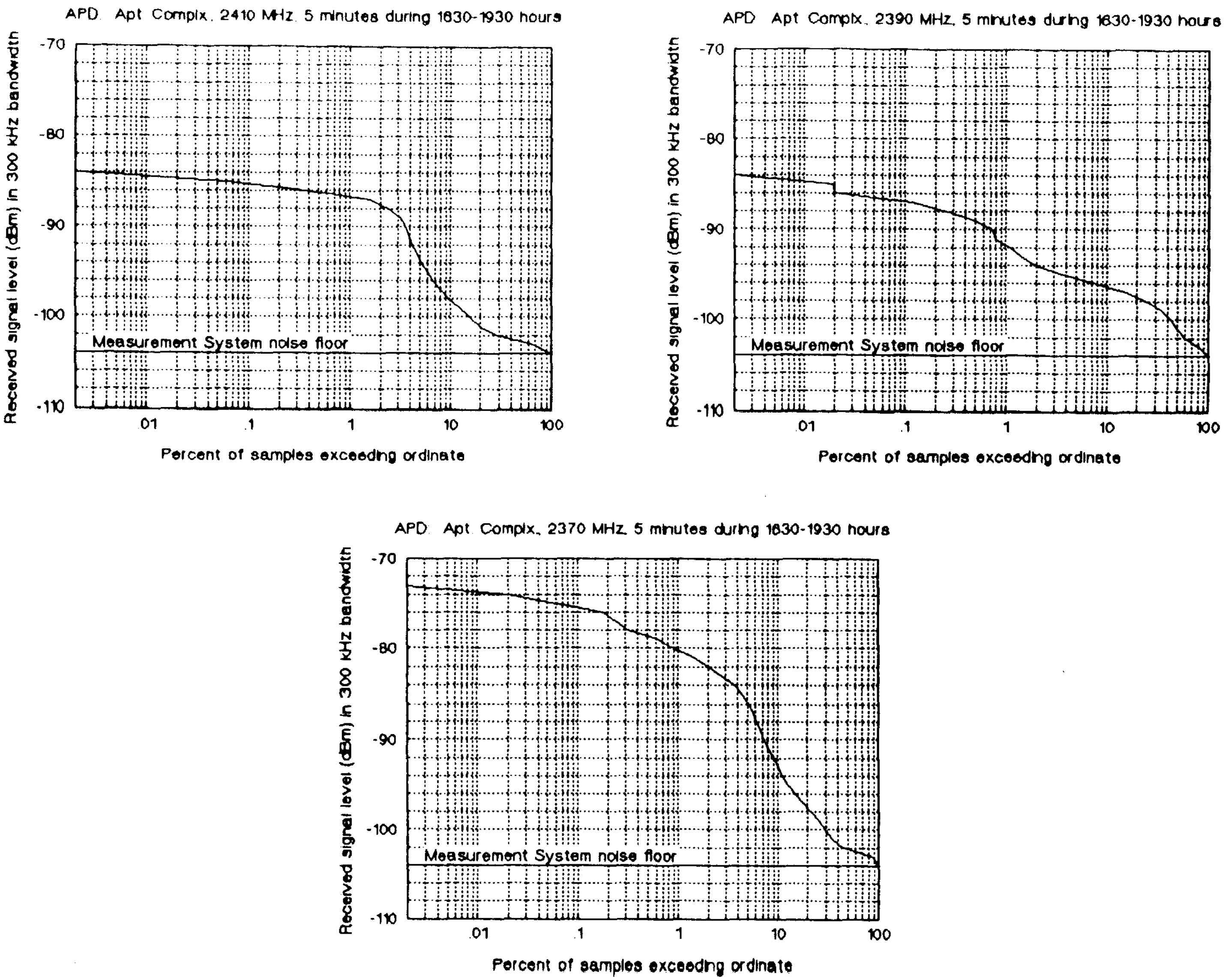

Figure 3-12. Apartment exterior amplitude probability distributions

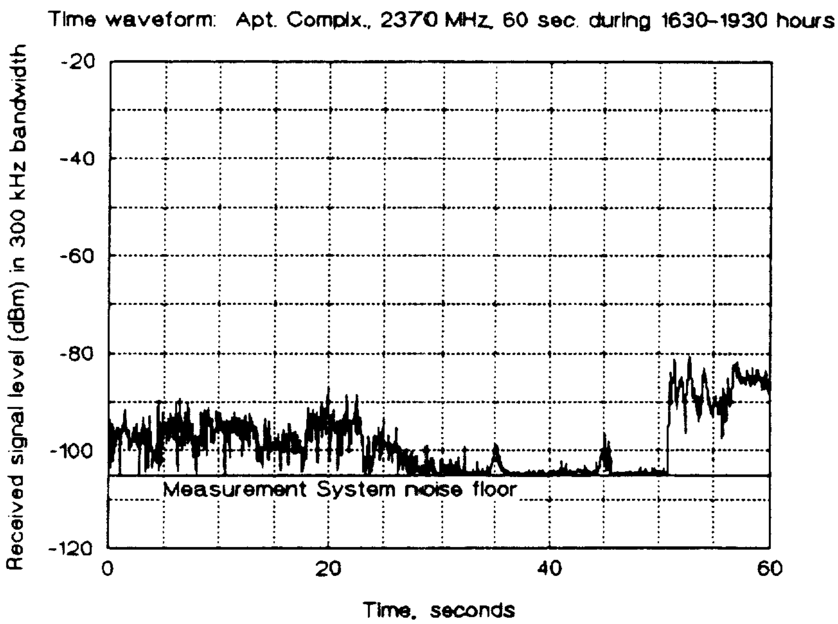

Figure 3-13. 60-Second time waveform outside apartment complex

SECTION 4

ACCOMMODATION OF MSS UPLINKS IN THE 2390-2450 MHz RANGE

INTRODUCTION

This section contains an analysis of the feasibility of accommodating geostationary MSS uplinks in the 2390-2450 MHz range. Measurements were made to identify the emission characteristics of the ISM environment and an analysis was performed to identify whether a segment of the range was suitable for MSS uplink operations.

MEASUREMENTS

Measurements were taken from two hilltops outside of Boulder, CO. to estimate the equivalent isotropic radiated power (EIRP) of the ISM environment. The hilltops at Green Mesa and Flagstaff are approximately 155 meters and 610 meters above the city. Green Mesa and Flagstaff are approximately 3.5 and 3.9 km, respectively, from the geographic center of the city; however, they are 2.3 and 3.5 km, respectively, from the closest concentration of significant radio emissions. The population of Boulder is approximately 90,000.

Three types of measurements were made: aggregate emission spectra across the band, aggregate signal amplitude distributions at fixed frequencies, and aggregate time waveforms at fixed frequencies.

Aggregate Emission Spectrum

A resolution bandwidth of 30 kHz[5] and a peak detector were used to measure the entire 2300-2600 MHz band. The band was swept in 5 seconds, measuring power in dBm, and the sweeps were continued for a period of 1 minute holding the peak values. At the end of each minute, the maximum levels were recorded in a data file as a single scan. During a 24 hour weekday period, 252 scans of this type were recorded (a scan consisting of 12 full-band sweeps). The resulting data were then used to plot cumulative wide band scan data including the maximum peak, mean peak, and minimum peak signal levels received at each frequency. Figure 4-1 and 4-2 show the data accumulated during the day at the two sites.

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5 The maximum bandwidth for an MSS channel is thought to be near 30 kHz.

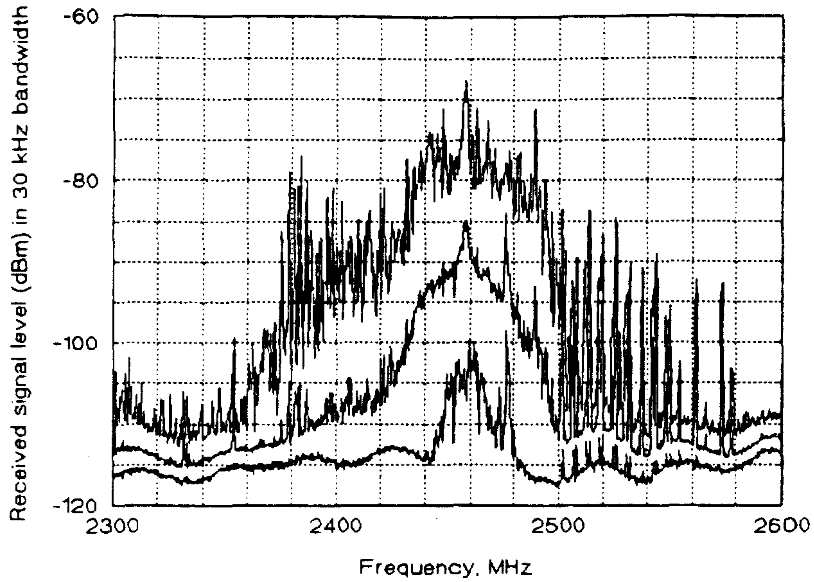


Figure 4-1. Aggregate emission spectrum from Green Mesa

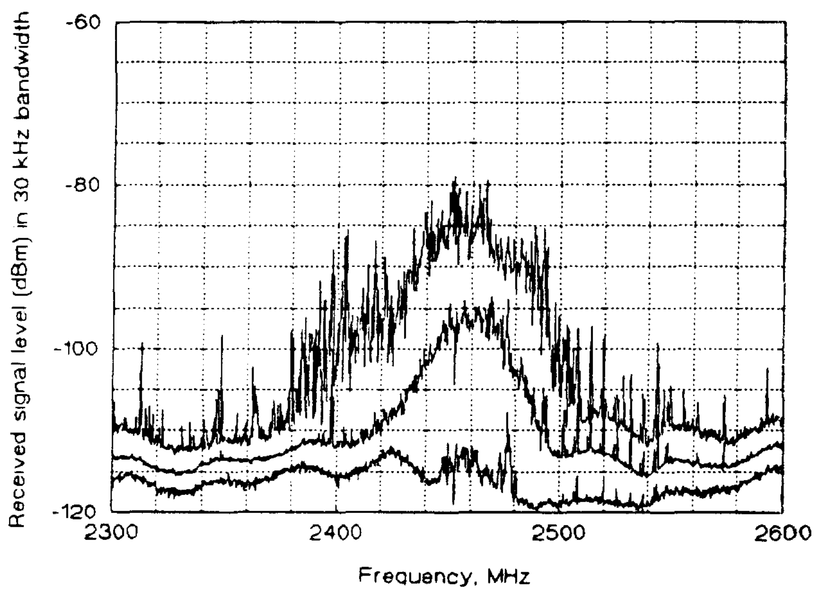


Figure 4-2. Aggregate emission spectrum from Flagstaff

Aggregate Signal Amplitude Distributions and Time Waveforms

Three 5-minute breaks were taken from the emission characteristic measurements, and the receiver was set for specific frequencies, 2410 MHz, 2430 MHz, 2450 MHz. During these 5-minute periods, 5000 samples of the incoming signal level were measured. The 5-minute periods were all taken during the breakfast period (6:00-9:00 AM) at Green Mesa. From this data, aggregate APDs were plotted. Figures 4-3 provides the data from Green Mesa. During the 5-minute periods at Green Mesa, the -75 dBm maximum peaks were not seen.

The APD for 2450 MHz shows a narrower range of variability of received signal level (≈21 dB) in comparison to the APDs at 2430 and 2410 MHz (≈ 27 dB). This indicates that the aggregate signal characteristics at 2450 MHz are more noise-like, and below 2450 MHz are more impulse-like. This is supported by the aggregate time waveforms in Figure 4-4.

ANALYSIS

The following is an analysis of the feasibility of accommodating MSS in the 2390-2450 MHz band based on the above measured data.

Boulder EIRP

To determine the potential degradation caused by an ISM environment, the aggregate EIRP at the satellite must be calculated. For the case of the transmitted wave coupled by free-space propagation, the received peak EIRP of Boulder is expressed as:

$$EIRP_B = P_r - G_r + L_p \tag{4-1}$$

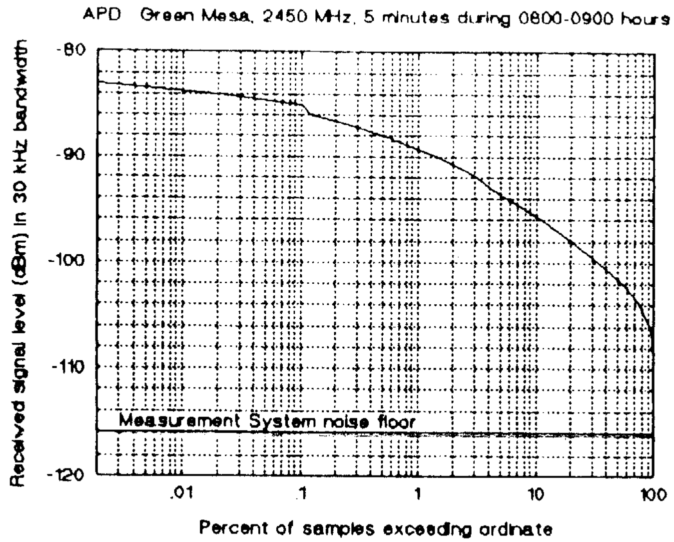
where:

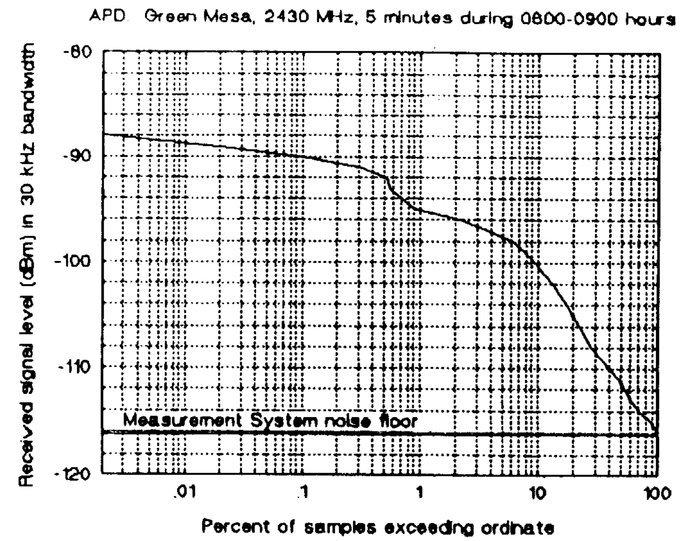
$EIRP_B$ = effective isotropic radiated power of the microwave ovens or other sources in the Boulder area, in dBm

P_r = received power at the measurement receiver input, in dBm

G_r = gain of measurement receiving antenna, in dBi (2 dBi for cavity-backed spiral)

L_p = free-space propagation path loss, in dB





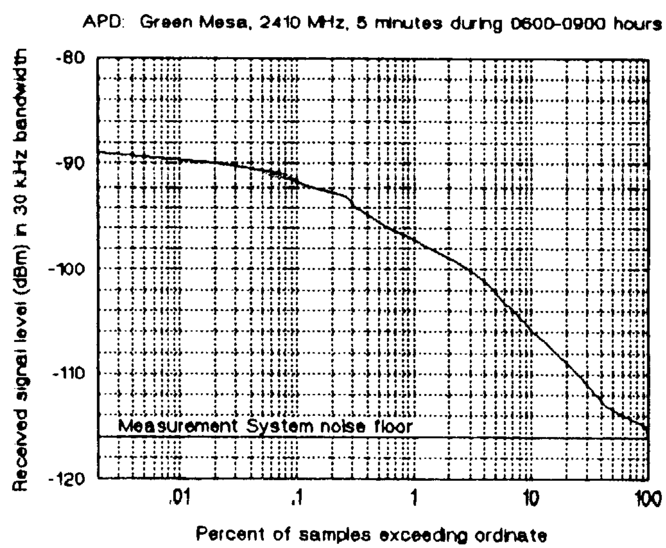


Figure 4-3. Green Mesa APDs

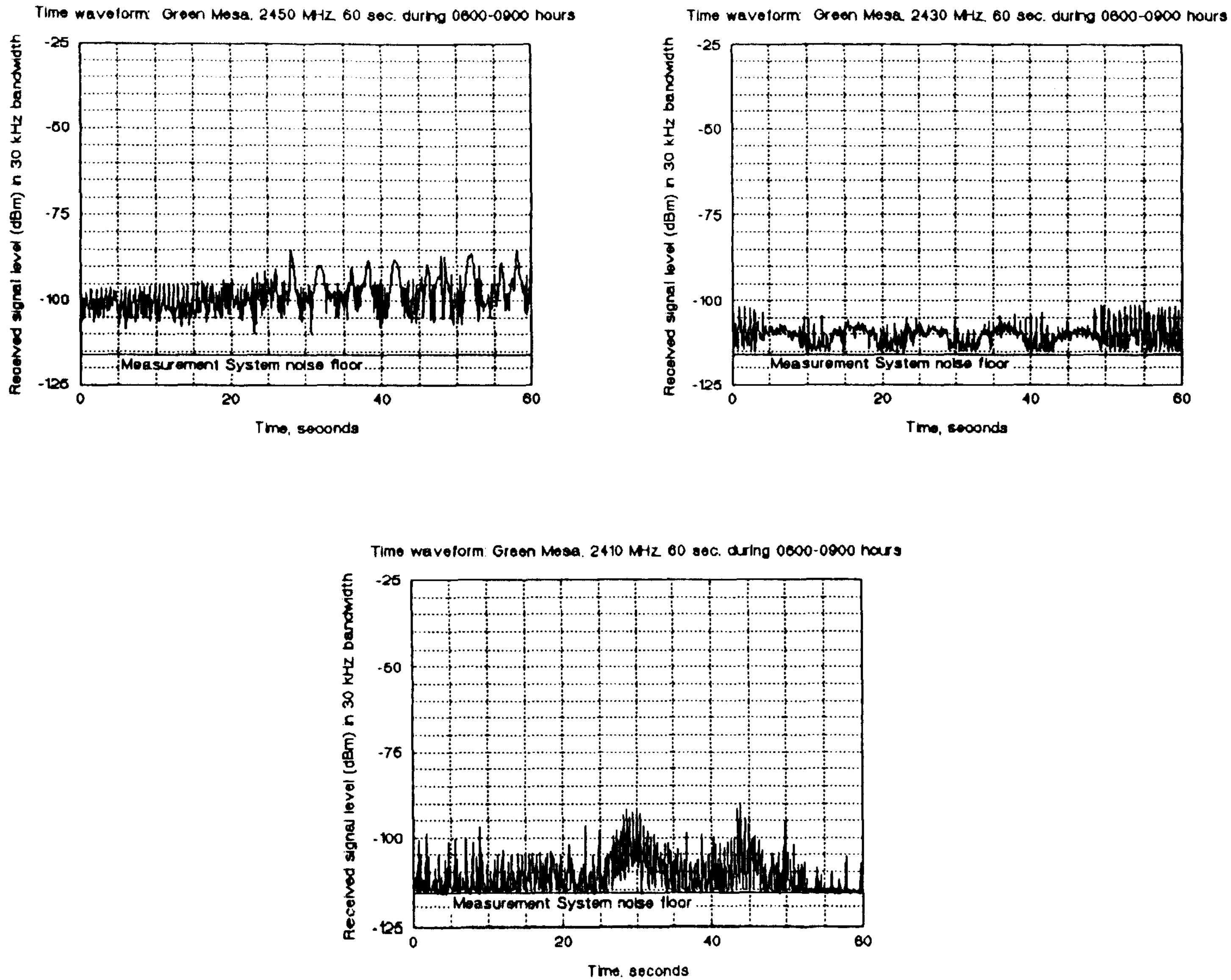


Figure 4-4. Green Mesa aggregate time waveforms

The Green Mesa measurements (Figure 4-1) showed a maximum peak power of -75 dBm occurred at 2450 MHz during the 24 hours measured. Computing the EIRP from the closest concentration of significant sources (2.3 km) results in the following.

$$EIRP_B = -75 - 2 + 107 \tag{4-2}$$

$$EIRP_B = +30 \text{ dBm @ } 2450 \text{ MHz} \tag{4-3}$$

Therefore, based upon these measurements at 2450 MHz, a maximum peak EIRP of 1 W appears to characterize an ISM environment of approximately 90,000 people.

The Flagstaff measurements (Figure 4-2) show a maximum peak power of -80 dBm occurred at 2450 MHz during the 24 hours measured. Computing the EIRP from the closest concentration of significant sources results in the following.

$$EIRP_B = -80 - 2 + 111 \tag{4-4}$$

$$EIRP_B = +29 \text{ dBm @ } 2450 \text{ MHz} \tag{4-5}$$

Once again, this approximates a maximum peak EIRP of 1 Watt.

If the geographic center of town is considered the point of radiation, the EIRP at 2450 MHz is +34 dBm as seen from Green Mesa and +30 dBm as seen from Flagstaff. Therefore, it appears that the city of Boulder, with a population of 90,000, can be characterized by an EIRP of +30 dBm at 2450 MHz.[6] In order to confirm the reasonableness of these values, a similar computation can be made extrapolating from the EIRP of a single oven to the number of ovens expected within the city of Boulder.[7]

$$EIRP_B = P_r - G_r - A_b + L_p + 10\log N \tag{4-6}$$

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6 There is some uncertainty in using measurements of Boulder to characterize an ISM environment for all cities of 90,000 population since Boulder is a research oriented business community. An area with more heavy industry may be different.

7 Where the aggregate emissions are noise-like, the extrapolation of the composite EIRP of large numbers of signal sources can be estimated via a 10logN relationship. As the aggregate signal becomes more impulsive, this relationship will be less valid.

where: $EIRP_B$ = effective isotropic radiated power of the microwave ovens or other sources in Boulder, in dBm

P_r = received power from a single oven at the measurement receiver input (See Figure 3-1), -13 to -30 in dBm

G_r = gain of measurement receiving antenna, in dBi (2 dBi for cavity-backed spiral)

A_b = building attenuation, in dB (at 2450 MHz typically 5 dB)

L_p = free-space propagation path loss for 3 meters, in dB

N = the number of ovens in Boulder hitting 2450 MHz at a specific instant

$$N = \frac{\text{pop. } 90{,}000}{2.5 \text{ pop. per household}} \times 80\% \text{ of households} \times .001 \text{ activity factor}^{8}$$

$$EIRP_B = -30 \text{ to } -13 \text{ dBm} - 2 - 5 + 50 + 14 \tag{4-7}$$

$$EIRP_B = +27 \text{ to } +44 \text{ dBm @ } 2450 \text{ MHz} \tag{4-8}$$

Factors such as a higher attenuation caused by buildings, or a smaller percentage of households with microwave ovens, a greater average people per household, or a lower activity level could bring these results closer to the values based on the aggregate spectrum measurements.

Figure 4-5 shows the Green Mesa measurements normalized in terms of EIRP, based on an EIRP of +30 dBm at 2450 MHz. From that figure, the maximum peak, mean peak, and minimum peak EIRP can be directly determined for any frequency in the range of interest.

The potential for interference is related to the probability of exceeding a given EIRP value. APDs for three specific frequencies are shown in Figure 4-3. For MSS, the acceptable bit error rate will probably be 10^{-3} for voice and 10^{-5} for data. From the APDs, acceptable bit error rates for data will only be met if the received signal level is above -82, -88, and -89 at 2450, 2430 and 2410 MHz, respectively. Normalizing these received signal levels to -75 dBm which equates to an EIRP of + 30 dBm, acceptable BERs can only be met if an EIRP of +23, +17 and +18 is not exceeded at 2450, 2430 and 2410 MHz, respectively.

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8 This estimated activity factor combines a percentage of ovens on at a particular time with the probability of a microwave oven transmitting on that frequency. In the case above, it was assumed that 1 out of every 100 ovens would be turned on at any particular time. Also, it was assumed that, due to pulse duty cycle and frequency variation, 2450 MHz was only hit 1/10th of the time.

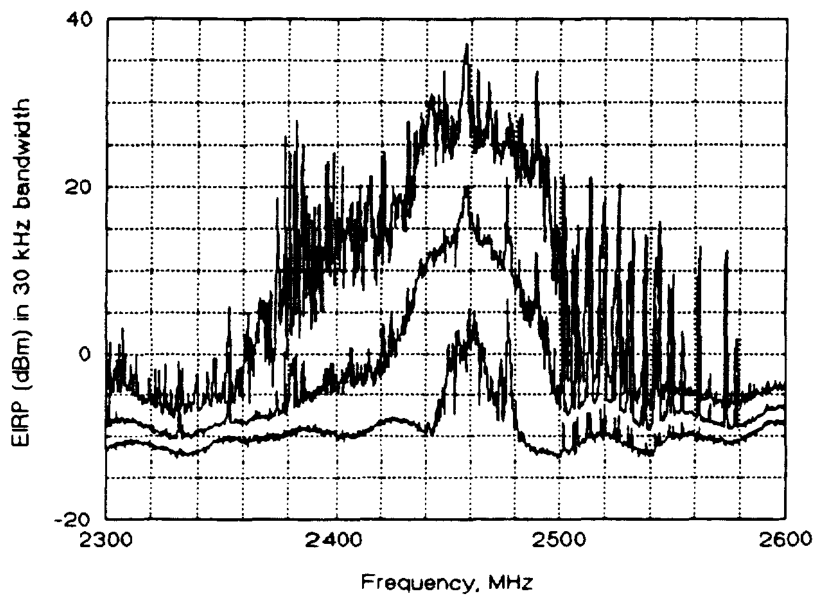

Figure 4-5. ISM environment EIRP for Boulder

Since the aggregate emissions appear noise-like, a mean squared (MS) signal level would probably be more useful. The maximum MS levels would be 12 dB below the maximum peaks or -87 dBm. This approximates what was seen during the 5-minute periods (See Figure 4-3).

Total Environment EIRP

An MSS satellite is assumed to have four antenna beams to provide service to the U.S. east coast, central, mountain, and west coast regions. Assuming that the EIRP of the ISM environment aggregate signal level will increase as 10 log N (See Note 7),

where: N = the ratio of total population/90,000

The EIRP of the ISM environment at 2450 MHz as seen by each antenna beam is determined by:

$$EIRP_{EC} = 30 \text{ dBm} + 10 \log 7X10^7 \text{ (approx. east coast pop.)}/9X10^4 \qquad (4\text{-}9)$$

$$EIRP_{EC} = 30 \text{ dBm} + 29 \qquad (4\text{-}10)$$

$$EIRP_{EC} = 59 \text{ dBm @ } 2450 \text{ MHz} \qquad (4\text{-}11)$$

C/I Analysis

The expected carrier-to-interference ratio (C/I) within a beam assumed to cover the east coast can be represented by:

$$C/I = EIRP_{MSS} - EIRP_{EC} \qquad (4\text{-}12)$$

If the EIRP of the MSS mobile transmitters is near 12 dBW and the beam will have to cover the east coast where the interfering EIRP is 29 dBW (59 dBm), the C/I becomes

$$C/I = 12 - 29 \qquad (4\text{-}13)$$

$$C/I = -17 \text{ @ } 2450 \text{ MHz} \qquad (4\text{-}14)$$

The MSS protection ratio will probably be near +20 dB. For some carrier types, the protection ratio may be as low as +15 dB, however, in such cases, the proposed system EIRP is also decreased.

Since, the aggregate signal appears noiselike at 2450 MHz, the mean square EIRP values may be more reasonable to use than the peak. The mean square EIRP will be approximately 12 dB less than the peak. Therefore,

$$C/I = 12 - (29 - 12) \qquad (4\text{-}15)$$

$$C/I = -5 \text{ @ } 2450 \text{ MHz} \qquad (4\text{-}16)$$

As seen in Figure 4-5, the EIRPs of the ISM environment is reduced by 10-15 dB below 2430 MHz.

$$C/I = -5 + (10 \text{ to } 15) \tag{4-17}$$

$$C/I = +5 \text{ to } +10 \text{ dB @ below 2430 MHz} \tag{4-18}$$

This is still below the protection ratio that will probably be required. However, the additive effect of increasingly impulsive emissions below 2430 MHz may be less than the assumed 10logN, improving the C/I ratio further. Also, the use of higher EIRP by the MSS mobile earth stations, robust forward error correction, and use of narrower satellite antenna spot beams may provide the needed improvement in the performance.

ANALYSIS SUMMARY

Above 2450 MHz, system performance requirements for MSS probably could not be achieved. In the 2390-2430 MHz range, there would be improvement in the achievable C/I because of lower microwave oven emission amplitude. Also, the impact of the oven pulses will be decreased because the increasingly impulsive characteristic of the aggregate will cause the additive effect to be less than the assumed 10logN. However, the emission levels may still be high for the use of handheld transmitters. Use of higher EIRP by the MSS mobile earth stations, robust forward error correction, and use of narrower satellite antenna spot beams may provide the needed improvement in the performance.

An MSS system appears feasible in the 2390-2430 MHz band if the emissions from ISM are given adequate consideration. Characterizing the maximum level of cumulative emissions that might be encountered within a single satellite beam by extrapolating from the Boulder, CO environment entails some uncertainties. Though aggregate measurements can account for the variables associated with single emitters, the aggregate environment of Boulder, a "high tech", research, and university oriented city, may be significantly different from an industrial city. Furthermore, the measurements, though taken on hilltops, may still not adequately represent the emission levels in a more vertical direction.

APPENDIX

BSS INTERFERENCE MARGIN ANALYSIS

1. Introduction

The Broadcasting Satellite Service (BSS) is expanding to provide high-quality sound broadcasts for fixed, mobile, and portable station reception. The user population will increase through wide area coverage and the sound quality will be enhanced via advanced digital modulation techniques. These provisions will jointly increase the service availability and quality delivered relative to the current status.

The service availability increase can be based on using terrestrial repeaters to fill stations coverage gaps otherwise inaccessible by satellite links alone. The new digital modulations can operate in the multipath environment created by terrestrial obstructions, and the satellite link can be power-limited to only support the regularly accessible areas.

Moreover, there is potential for a shared-band operation of satellite and terrestrial broadcasting services. A receiving station may be designed to accept either satellite or terrestrial transmissions, and these two services can coordinate shared channel operations to maximize spectrum use efficiency. Such channel reuse will also help to standardize the broadcasting service technology and developments to jointly support both terrestrial and satellite services.

2. Digital Modulation Systems

There have been five modulation systems identified to support the BSS. Two of them are analog, namely Conventional FM and Companded FM. The other three are digital, and referred to as Simple Digital (VSB/BPSK), Advanced Digital II (COFDM/4DPSK), and Advanced Digital III (SCPC/4CPSK).

The two FM Systems and the Simple Digital System are intended for monophonic sound, while the two Advanced Digital Systems (ADSII, ADSIII) can also support stereophonic sound broadcast. The Advanced Digital systems can also deliver a higher quality grade (4.5) with 180-256 kbps per stereo program, and can support a wider audio baseband (20 kHz) than the other systems. A capacity of 12 stereo channels is supported in a 3 MHz total bandwidth with 220 kbps per stereo channel, or in 3.5 MHz with 256 kbps per stereo channel.

ADSII employs an orthogonal frequency-division multiplexing scheme (OFDM), along with convolutional coding (COFDM) and time interleaving. The information is distributed among multiple 4 DPSK subchannels per single-channel broadcast, in order to create frequency diversity and combat frequency-selective fading. This frequency interleaving is augmented by time interleaving to provide a flexible system specification towards multipath protection.

All the quaternary DPSK subchannels involved are demodulated and combined to recreate the single-channel baseband at the receiver, with FFT algorithms employed to expedite processing. A total number of 448 7.8-kHz subchannels has been identified to support 12 stereo channels in a 3.5 MHz bandwidth, which corresponds to about 290 kHz per stereo channel spread.

ADSIII employs a SCPC approach, with offset quaternary CPSK modulation and coherent demodulation per channel, along with time interleaving, convolutional coding, and adaptive equalization to combat multipath. Hence, a single stereo channel occupies 290 kHz of the 3.5 MHz needed for 12-channel support with 256 kbps.

ADSII has undergone extensive air testing in Canada and Europe to demonstrate its capabilities. ADSIII is still under development in the United States, and has yet to be tested experimentally to establish the extent to which the theoretical advantages of coherent detection can be achieved in practice.

3. Interference Margin Analysis

The threshold margin for external interference is analyzed in this section by investigating: (a) the total (noise-plus-interference) input threshold level; (b) the actual received input noise level; (c) the input interference level margin thus allowed. The analysis essentially assumes a white-noise characterization for the interference spectrum over the receiver passband.

The performance requirement has been specified in Reference 1 as a digital output SNR of 7.5 dB to produce a 10^{-3} BER in the data extracted. This value has been noted as theoretically and experimentally verified for the ADSII System, and may be further relaxed for the ADSIII System pending the coherent detection improvement capabilities after implementation.

This output SNR requirement becomes a nominal input SNR requirement of 60.9 dB-Hz for a 220 kbps data rate when processing losses are neglected. A realistic input SNR requirement has been noted to be 67.3 dB-Hz per stereo channel, when accounting for 6.5 dB miscellaneous processing losses (4 dB implementation, 0.5 dB uplink degradation, 2 dB frequency reuse).

These input and output SNR requirements must accommodate both thermal noise and external interference effects; i.e., a $E_b/(N_o + I_o)$ = 7.5 dB output performance requires a $C/(N_o + I_o)$ = 67.3 dB-Hz input level. This implies a C/(N + I) = 2.5 dB requirement in a 3 MHz bandwidth needed to support 12 stereo channels with 220 kbps, or a 12.5 dB requirement in a 300 kHz bandwidth for a single channel.

The actual received noise levels will first be computed for a 1 GHz down-link frequency, and the results will then be extrapolated to other frequencies as done in the CCIR study. This approach facilitates understanding the current link budget specifications and the parametric variation rationale with link frequency. The basic approach in the CCIR study is to compensate for higher fade margins and tranmission losses via higher satellite transmitter powers as frequency increases.

3.1 CCIR Link Budget and Interference Margin at 1 GHz

The 1 GHz link budget is presented in TABLE 1, with the parameter values representing CCIR study specifications in Reference 1. The approach is to consider three satellite beams representing distinct service area coverages, and the satellite transmitter power is adjusted to absorb the on-axis antenna gain variation and maintain a constant EIRP.

The propagation and receiver parameters are invariant with the beam coverage. The propagation distance and free-space loss values shown in the table correspond to the 163 dB/m^2 spreading loss specified in the CCIR document. The 5 dB fade and 3-dB contour conditions in the received C/N_o level are also documented in the CCIR document.

The received signal level can be computed from the table as C = −107 dBm, including the 5 dB signal fade and the 3 dB mainbeam edge loss relative to on-axis antenna gain. The received thermal noise level is N_o =−174.2 dBm-Hz, as derived from the noise temperatures and receiver parameters specified.

The received C/N_o level breakdown illustrates that the system is already essentially operating at threshold (67.3 dB-Hz) without external interference if: (a) the 5 dB signal fade occurs, (b) the receiver is located at the 3 dB mainbeam edge, (c) the 2 dB frequency reuse protection is required. In other words, the external interference must be negligible relative to thermal noise since there is no system performance margin with this link budget if those three conditions exist.

For example, if a 1.0 dB maximum interference degradation is identified to mean negligible, then the interference level would be required to be about 6 dB below the thermal noise level. The latter is N_o = −174 dBm-Hz, so the interference level could not exceed

TABLE 1

CCIR 1 GHz LINK BUDGET SPECIFICATIONS

Satellite Beam Coverage (deg)	1	1.6	3.5
Satellite Antenna On-Axis Gain (dBi)	44.3	40.2	33.4
Satellite Transmitter Power (W)			
per Stereo Channel	4.1	10.5	50
for 12 Stereo Channels	49	126	600
Satellite EIRP (dBW)			
per Stereo Channel	50.4	50.4	50.4
for 12 Stereo Channels	61.2	61.2	61.2
Propagation Distance (km)	39850	39850	39850
Free-Space Propagation Loss (dB)	184.4	184.4	184.4
Receiver Antenna Gain (dBi)	5	5	5
Receiver Antenna Noise Temperature (K)	105	105	105
Receiver Noise Figure (dB)	1	1	1
Receiver Coupling and Filter Losses (dB)	1	1	1
Receiver System Noise Temperature (K)	276.4	276.4	276.4
Receiver Figure of Merit (dB/K)	-19.4	-19.4	-19.4
Receiver Thermal Noise Density (dBm-Hz)	-174.2	-174.2	-174.2
Receiver Noise Level in 3 MHz (dBm)	-109.4	-109.4	-109.4
Receiver Noise Level in 300 kHz (dBm)	-119.4	-119.4	-119.4
Required C/N_o per Stereo Channel (dB-Hz)	67.3	67.3	67.3
Actual C/N_o on Mainbeam Axis and No Fade	75.2	75.2	75.2
Actual C/N_o on Mainbeam Axis and 5 dB Fade	70.2	70.2	70.2
Actual C/N_o on Mainbeam Edge and 5 dB Fade (per Stereo Channel)	67.2	67.2	67.2

Note: The received signal level in all cases is C = -107 dBm per stereo channel when the 5 dB signal fade and 3 dB mainbeam edge operation is assumed.

I_o = −180 dBm-Hz, or I = −125 dBm in a 300 kHz bandwidth and I = −115 dBm in a 3 MHz bandwidth.

Conversely, if the aforesaid conditions (5 dB signal fade, 3 dB mainbeam edge, 2 dB reuse protection) can be relaxed, a higher interference level can be accepted since a system performance margin would then exist. Alternately, these conditions could be assumed while also increasing the satellite transmitter power from the CCIR specifications, so as to create a system performance margin while maintaining the performance threshold invariant.

However, the improvement potential is rather limited while maintaining a realistic satellite transmitter power specification. The state-of-the-art technology is identified as about 1.5 kW in the CCIR document, and it has been noted by the United States Information Agency (USIA) that the cost associated with such value would be economically impractical to support only 12 stereo channels. A 75-channel support is expected, and this would represent a maximum of 1500/75 = 20 W per stereo channel.

Note that a 20 W transmitter power per stereo channel would not suffice for the 3.5° beam coverage (see TABLE 1). For the other cases, it would create a system performance margin (I+N/N) of 8.5 dB for the 1° beam coverage, and 2.8 dB for the 1.6° beam coverage, which correspond to an interference margin (I/N) relative to noise of 7.8 dB (1° beam case) and −0.4 dB (1.6° beam). The interference levels allowed would be −112 dBm (1° beam) and −120 dBm (1.6° beam) in a 300 kHz bandwidth, or −102 dBm (1° beam) and −110 dBm (1.6° beam) in a 3 MHz bandwidth.

3.2 CCIR Link Budget and Interference Margin at 2.4 GHz

The CCIR approach to account for distinct link frequencies is to have the satellite transmitter power compensate for the variation of frequency-dependent parameters. These are essentially the signal fade and the transmission loss effects, whose required compensation relative to 1 GHz is shown in Figure 1.

The added compensation ranges from -7.5 dB (less transmitter power) at 0.5 GHz to 13.2 db (more transmitter power) at 3.0 GHz relative to the 1 GHz link condition. Other link parameters remain invariant with frequency, except for the system noise temperature which exhibits a negligible variation (within 0.4 dB in the 0.5 to 3.0 GHz range).

The net effect is that the transmitter power requirement becomes increasingly higher with link frequency; e.g., a 10.2 dB increase is required at 2.4 GHz relative to the 1 GHz value. The total power required at 2.4 GHz for 12 stereo channels would be 513 W for the 1° beam coverage, 126 W for the 1.6 beam coverage, and 6300 W for the 3.5° beam coverage.

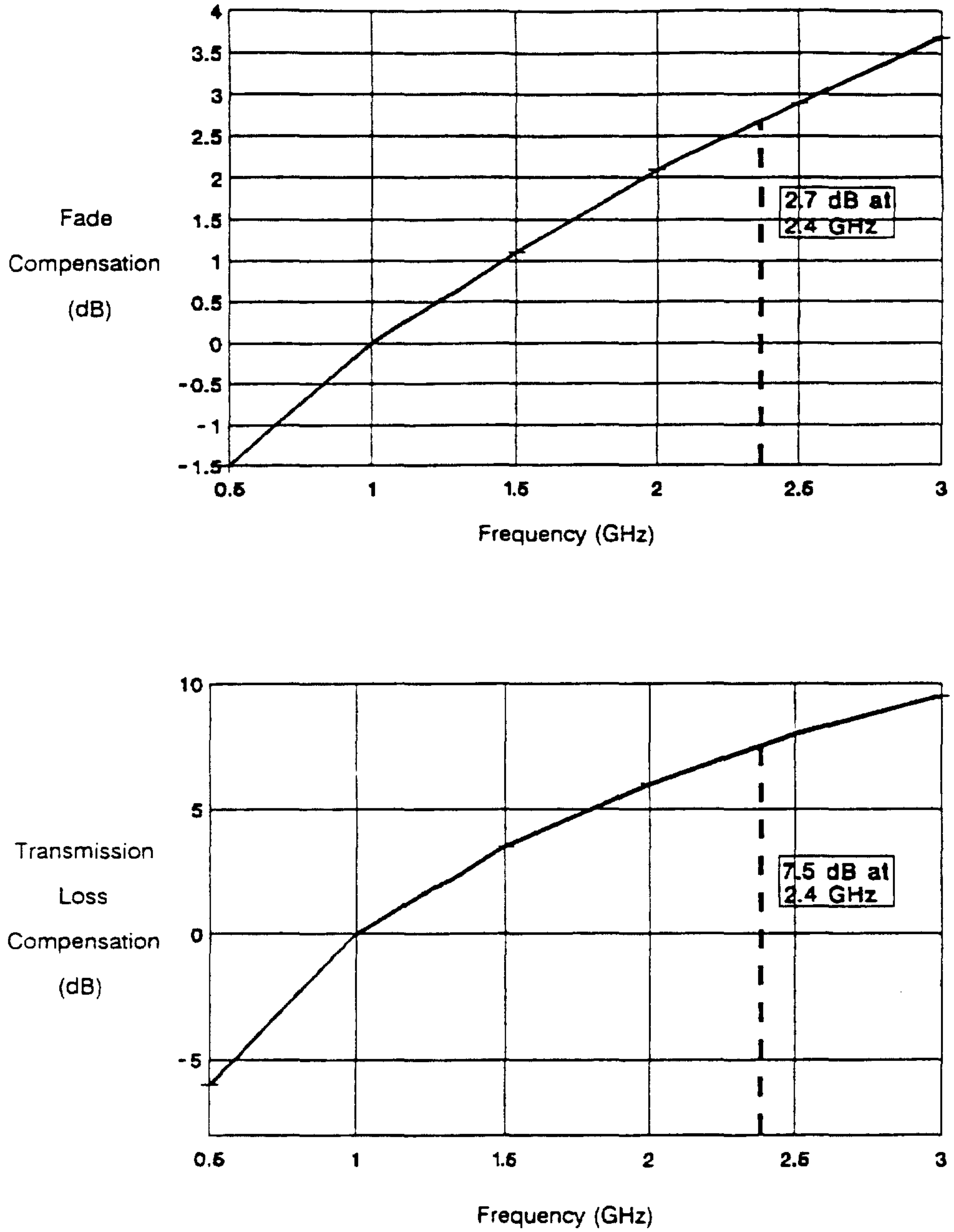

Figure 1. Frequency dependent compensation

The 3.5° beam requirement exceeds the present and projected state-of-the-art. The other cases require 43 W per stereo channel for the 1° beam, and 108 W per stereo channel for the 1.6° beam. These values exceed the 20 W maximum allowed for a 75 channel capacity, and would imply a reduction to 35 (1° beam) or 14 (1.6° beam) stereo channels. Moreover, there would still be no system performance margin, and negligible interference would be required (e.g., −125 dBm in 300 kHz or −115 dBm in 3 MHz for a 1 dB degradation criterion).

An implementation limit for the satellite antenna diameter has also been cited as 10 meters for state-of-the-art and 20 meters for the future. This would restrict the satellite antenna beamwidth to be greater than 2° at 1 GHz and 1° at 2.4 GHz for state-of-the-art, or 1° at 1 GHz and 0.5° at 2.4 GHz for the future.

3.3 ADSII Interference Margin Improvement

The 67.3 dB-Hz performance threshold has been documented in Reference 1 as applicable to both ADSII and ADSIII. The corresponding protection ratio is 12.5 dB in 3 MHz, yet a relaxed protection by about 5.5 dB has also been reported for ADSII in Reference 2. The system designer in France reiterated this claim when contacted by NTIA.

If this Reference 2 protection is assumed, the interference allowance (I/N) is 4 to 5 dB relative to noise. This represents interference levels allowed of about −115 dBm in 300 kHz, or −105 dBm in 3 MHz, assuming the carrier and noise level magnitudes remain invariant.

3.4 Summary and Conclusions

There are four generic modulations identified for potential BSS support. Conventional FM is presently employed, and companded FM, simple digital, or advanced digital systems represent potential candidates. The advanced digital systems (ADS) have been identified as a major interest, though there is still support by administrations to preserve the analog FM system(s).

ADSII and ADSIII represent the current ADS candidates. Both deliver higher quality sound grade and support multiple stereo channels. Modern source coding is employed to reduce data rates and information bandwidth, along with frequency and/or time interleaving to control selective fading and combat multipath to permit service zones otherwise not supported.

ADSII decomposes each 300 kHz stereo channel into many narrower components spread throughout a 3.5 MHz link bandwidth for a 12 channel capacity, with the other channel components interleaved in-between. ADSIII employs a SCPC approach for the 12-channel multiplexing in a 3.5 MHz link bandwidth. ADSII has been tested with success in Canada and Europe, whereas ADSIII is still under development in the United States.

A similar typical link budget has been identified by CCIR for both ADSII and ADSIII (Reference 1). Various link frequencies are considered in the 0.5 to 3.0 GHz range, and the system performance margin is 0 dB in all cases. This includes a 2 dB allowance for internal interference within the system, but any other external interference has to be negligible relative to noise.

A potential increase in the satellite transmitter power was considered to increase the margin and permit more external interference. However, there is a further limitation introduced by the concern of providing a 75 stereo-channel capacity for economic considerations. This would restrict the power per channel to 20 W with a 1500 W state-of-the-art transmitter.

The net result is that an external interference margin can be created at 1 GHz for narrow (1°, 1.6°) satellite antenna beams, but not at 2.4 GHz. The latter would require a reduction in stereo-channel capacity to 35 (1° beam) or 14 (1.6° beam) channels just to maintain the 0 dB system performance margin. This happens because the higher signal fades and transmission losses must be compensated by higher transmitter power as the link frequency increases.

This status requires the external interference to be negligible at 2.4 GHz, along with the reduced channel capacity. If a 1 dB degradation is identified as the negligible allowance (I/N = −6 dB), then the interference level limit is −125 dBm in 300 kHz, or −115 dBm in 3 MHz. An additional 5.5 dB margin improvement has been reported (Reference 2) for the ADSII system by its designer in France, in which case the new interference allowance (I/N = 4 to 5 dB) would represent limits of −115 dBm in 300 kHz, or −105 dBm in 3 MHz.

REFERENCES

1. CCIR Document JIWP92/115-E.

2. CCIR Report 955-2.